Laboratory Electron Exposure of TSS–1 Thermal Control Coating
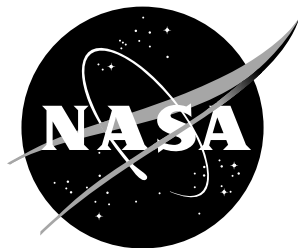
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LABORATORY ELECTRON EXPOSURE OF TSS-1 THERMAL CONTROL COATING

INTRODUCTION

The first mission of the tethered satellite system (TSS-1) flew on the space shuttle mission STS-46 on July 31, 1992, which included both the deployment of the EURECA satellite and the EOIM-3 payload. The TSS-1 encountered problems during deployment of the satellite and was not able to meet all of its objectives, and a reflight of the TSS-1 has been approved.

The TSS-1 payload was designed with two primary objectives: (1) study tether dynamics in space and (2) study the electrodynamics of a conducting tether in space. Tether electrodynamics involves generating a potential along the metallic tether as it cuts through the Earth's magnetic field and investigating the electron current flow through the plasma, as well as the electron plasma sheath at the satellite. Current flow along the tether is possible if sufficient coupling to the space plasma at both ends of the tether exists. In the case of the TSS-1 payload, an electron gun was placed aboard the shuttle to emit electrons. The satellite at the other end of the tether was required to collect electrons from the plasma, which is possible if the potential applied by the tether is greater than the ambient plasma potential and the satellite skin is conductive. The satellite skin conductivity must be large to maximize electron current collection by limiting the resistance at the satellite skin. The high conductivity requirement can be met with any metal; however, the satellite has thermal requirements which precludes metals since they do not have the emissive properties to radiate heat to the environment. In order to meet the conductivity and thermal requirements, the satellite skin had to be coated with a conductive thermal control coating. Such coatings have been developed for control of spacecraft charging. The satellite skin was initially coated with the thermal control coating, NS43C, which met all thermal requirements. However, it did not maintain sufficient conductivity in vacuum to meet the higher current requirements of the TSS mission. A special thermal control coating was developed and applied at Marshall Space Flight Center (MSFC), which met both the conductivity and thermal requirements and allowed the TSS-1 electrodynamic science objectives to be met.

The thermal control coating developed at MSFC, RM400, passed all qualification and acceptance test requirements. Included were numerous tests to understand the effects of atomic oxygen (AO), ultraviolet (UV) radiation, thermal cycling, plasma, and high energy electrons on both the conductivity and thermal properties of the coating. Because of the length of the tether (20 km), it generates several thousand volts when fully deployed. Electrons are accelerated from the ambient space plasma and impact the conductive thermal control coating with up to a few keV of energy. The thermal control coating was exposed in the lab to electrons with energies ranging from 0.1 to 1 keV to study the effect on the coating. During those tests, the coating was found to luminesce, and prolonged exposure of the coating to high energy electrons (~1 keV) caused the coating to darken. This report describes the tests done to quantify the degradation of the thermal control properties caused by electron exposure and to measure the luminescence as a function of electron energy and current density to the satellite.

EXPERIMENTAL TEST FACILITIES

The evaluation of the effects of exposing the RM400 thermal control coating to high energy electrons was done in two separate tests. The first experiment was designed to quantify the luminescence of the coating caused by electron exposure, and the second experiment was done to quantify the effects of electron exposure on the coating's thermal control properties (i.e., solar absorptance and infrared emittance). Both tests were done at MSFC in a diffusion-pumped vacuum chamber having a thermal argon plasma. The plasma generally had a density of 10^6 cm^{-3} and an electron temperature of 1 to 2 eV. The base pressure of the vacuum chamber was in the high 10^{-8} torr range and 10^{-5} torr with plasma source operating. The plasma in the chamber was generated using a hollow cathode[1] plasma source because of the long life and simplicity of the setup. Because oxygen exposure to the hollow cathode low work function internal surface poisons the cathode, the tests were limited to an argon plasma. Because our interest is primarily with the electrons, the ion species is somewhat immaterial.

The two different test setups in this evaluation are shown in figures 1 and 2. Figure 1 shows a detailed schematic of the test configuration used to evaluate the amount of light being emitted from the sphere during electron exposure. A 3.8-cm diameter sphere coated with the same RM400 coating applied to the TSS-1 skins was placed in the center of the plasma chamber and connected to a 1-kV power supply through a feedthrough isolated from the chamber walls. A grounding screen of varying diameters was placed around the sphere to prevent the electric field from growing too large and drawing very large currents. By varying the size of the grounding screen, the effects of varying the electron current density on the luminescence could be studied. The sphere luminescence was measured using a photodiode sensitive from 200 to 2,500 nm. This particular study looked only at the luminescence in the visible range (500 to 700 nm) by placing a 90-percent transmitting filter with the appropriate bandpass in front of the diode. During the tests, the sphere was biased from 0 to 1,000 V, and the current data from the sphere and diode were measured at each voltage increment. The diode current data were converted to irradiance data using the correlation data provided by the diode manufacturer.

Figure 2 shows a detailed schematic of the test setup used to expose several 2.54-cm diameter disks coated with RM400 to evaluate the effects of high energy electron exposure on the thermal control properties. The samples were placed in a specially designed sample holder to ensure that the electrons were accelerated normal to the surface. The samples were placed in the plasma and biased to either 175, 500, or 1,000 V and left over a period of time to accumulate the correct electron fluence. The thermal control properties were to be evaluated based on both a nominal and a worst case estimate of the electron dose for the TSS-1 mission. A typical orbit profile was examined, and a nominal and worst-case electron fluence during the mission was estimated to be 10^{17} electrons/cm^2 and 10^{18} electrons/cm^2, respectively. Electron fluences of these magnitude are accumulated in the plasma chamber in a matter of a few hours. The sample bias and electron current were computer monitored in order to stop the test at the appropriate point.

Figure 3 is a cross-sectional schematic of the sample holders used in these tests. The sample holder was designed to bias both the sample and a guard to the same potential to eliminate the effects of fringing electric fields. The grounded case and screen were designed to limit the distance the electric field grew into the plasma, which limited the amount of electron current collected. A separate wire is attached to both the guard and the sample to measure only the electron current to the sample itself. The spacing between the guard and the sample is very small to maintain a uniform electric field. Figure 4 is a photo of a typical sample holder before and after assembly. A completely assembled sample holder is presented in the center

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top of the photograph and the pieces which make up the sample holder are shown surrounding the assembly.

LUMINESCENCE TEST RESULTS

The luminescence characteristics of the RM400 thermal control coating were not observed during the initial development of the coating because initial measurements were limited to bias potentials of a few tens of volts. Because the TSS-1 payload was to be exposed to electrons having energies on the order of a few keV, the coating was exposed to electrons with energies in this range to assess any effects. In order for the sphere to be biased thousands of volts in a plasma, a grounding screen was introduced to limit electric field expansion from the sphere. Once the sample was capable of being biased above 300 to 400 V, the luminescence of the sphere was visible to the naked eye.

Three grounding screens of various diameters were used to study the effects of varying the electron current density to the sphere on the luminescence intensity. The sphere was biased from 100 to 1,000 V in 100 V increments, and electron current collected by the sphere at each voltage was measured. Typical current and voltage data for the sphere with the three different diameter (60-, 69-, and 81-mm) grounding screens can be seen in figure 5. The technique used to vary the bias to the sphere tended to add noise to the data. The noise caused by the bias voltage can be seen particularly in the data taken using the 60-mm diameter screen (open square data points) at the lower bias voltages where two different current values at the same voltage were recorded. The current collected using the 60- and 69-mm diameter screens did not show any noticeable change in magnitude probably due to a variation in plasma conditions, but the 81-mm diameter screen showed a noticeable increase in current collection, as would be expected.

Figure 6 is a photograph of the glowing sphere biased at 750 V with a 69-mm diameter screen. The faint outer sphere surrounding the glowing sphere is the grounding screen. The unusual pattern seen on the sphere is not discoloration on the sphere itself but variations in the intensity of the light coming from the sphere. The cause of the variation is possibly due to unevenness in the grounding screen surrounding the sphere focusing more electrons onto certain portions of the sphere or nonuniformity in the coating itself. Because the screens were difficult to fabricate and maintain a perfect sphere, the first scenario is considered most plausible.

Measurements of the light illuminating from the sphere were made using the photodiode with a 500- to 700-nm filter. The diode generates current based on the amount of photons hitting the diode. Using the amp to watts conversion provided by the manufacturer, the irradiance can be calculated. Figure 7 shows irradiance data calculated from the current data taken from the photodiode plotted as a function of the bias applied to the sphere with three separate grounding screens. The diode biasing current was subtracted from the data. The data shown in figure 7 indicated that even while the current collected by the sphere with the three different screen sizes varies by up to a factor of 3, there appears to be no corresponding change in the luminescence. This result suggests that the visible luminescence is dominated by the energy of the incoming electron energy relative to the range of current densities studied in these experiments.

THERMAL CONTROL PROPERTY CHANGES

After the luminescence measurements were completed, the sample was removed from the chamber and found to have darkened significantly. This became a concern because any darkening indicates changes in the thermal control properties. A matrix of tests were conducted to expose coated aluminum disks to high energy electron fluxes and to determine the effects of energy and electron fluence on the solar absorptance (α) and infrared emittance (ε). The previously discussed nominal and worst-case fluences were used. Prior to electron exposure, the samples were exposed to the anticipated AO fluence for the expected duration of the mission in order to make the tests more representative of what would be expected from flight.

The changes in the solar absorptance (α) and infrared emittance (ε) caused by the AO exposure and subsequent electron irradiation tests are shown in table 1. The solar absorptance for these tests were measured using both the Beckman DK-2 spectral reflectometer and the AZ Technology laboratory portable spectral reflectometer (LPSR) over the wavelength range 250 to 2,500 nm and infrared emittance measurements were made using the Gier-Dunkle DB-100 infrared reflectometer. The RM400 coated disks in these tests were coated from a different batch of paint than used to coat the flight skins. This is the reason for the difference between the initial solar absorptance values shown in table 1 and the 0.5 value for the flight skins. The data presented in table 1 are a summary of the results after each subsequent exposure listed. The first sample (RM-1) was held as a control and not exposed to any environments. RM-2 and RM-3 were exposed to AO only. RM-2 was exposed to thermal AO and RM-3 to a 5-eV neutral AO beam.[2][3] The remaining samples were all exposed to thermal AO and then the electron fluence and energy listed in the table. The two samples exposed to high energy electrons at the higher fluence turned visibly brown, while the others changed slightly. One interesting point is that the infrared emittance changed due to AO exposure but not due to electron exposure. This may be caused by the AO cleaning and eroding the binder, exposing more of the pigment. Figure 8 shows the effects that varying the electron energy has on the change in solar absorptance. At the nominal electron fluence expected for the TSS-1 mission, only slight changes in α would be expected with no noticeable darkening. For the worst case electron exposure, the high energy electrons above 500 eV would cause noticeable darkening of the RM400.

A final quantitative test was performed to see if the darkened coating would be affected by exposure to AO. The disk labeled RM-9 in table 1, which had the largest change in solar absorptance due to high energy electron exposure, was exposed to thermal AO in a conventional plasma asher. RM-9 was exposed for a total of 10 min in varying intervals to AO at a nominal flux of 10^{18} atoms/cm²-s. At the end of each interval, solar absorptance and infrared emittance measurements were made. Figure 9 shows the diffuse spectral reflectance curves measured on sample RM-9 after accumulating the amount of time listed in the legend. These data show that the effects of darkening of RM400 by electron exposure can be offset by AO erosion of the damaged surface. Figure 10 shows the changes in both solar absorptance and infrared emittance for sample RM-9 as a function of AO fluence. This figure shows the darkening of the sample to be completely converted back to the original solar absorptance at a fluence of 4×10^{20} atoms/cm². Also, the infrared emittance did not change significantly due to AO exposure. The AO fluence observed by the TSS-1 satellite during the STS-46 mission was on this order of 6×10^{19} atoms/cm², which does not include any exposure during both the launch of the EURECA satellite and the EOIM-3 mission phase. It should be pointed out that prior to the TSS-1 flight the AO fluence was predicted to be on the order of 2×10^{20} atoms/cm². However, due to the shortened mission, TSS-1 received a lower AO fluence. Should the

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RM400 see high energy electron fluences on-orbit capable of causing the coating to darken, the AO exposure would tend to reverse the process.

SEM photographs were taken of samples RM-1, RM-3, and RM-9. RM-1 is the control disk which was not exposed to any environment, RM-3 was exposed to a 5-eV AO neutral beam, and RM-9 was exposed to AO and 500 eV electrons. The surface of RM-1 appeared to be more coarse than the other two. This suggests that the AO appears to be smoothing out the surface causing the initial change in the emittance. RM-9 showed no effect due to the electron exposure it received. This suggests that the darkening of the coating is a chemical change taking place in the coating. The fact that the coating can be cleaned by AO exposure suggests that the chemical change is in the very thin top surface layer of the coating.

DISCUSSION

Exposure of the TSS-1 thermal control coating, RM400, to high energy electrons causes the coating to luminesce and if maintained for long periods of time will cause the coating to darken. The luminescence of RM400 was found to be a function of electron energy with light first being visible to the naked eye at 300- to 400-V bias on the sphere. The intensity of the luminescence was measured with three different size grounding screens, which changed the current density to the sphere, with no perceptible change observed. The RM400 paint turned noticeably dark when exposed to 500- and 1,000-eV electrons at a fluence of 10^{18} electrons/cm^2. At nominal mission electron fluences, there is minimal effect, additionally, the darkened surface is cleaned when exposed to AO. Depending on the AO and electron exposure, it is possible that the darkening caused by the electron exposure and the cleaning by the AO would not cause any noticeable change in any surface exposed to AO. Surfaces not exposed to AO will still be subjected to possible darkening caused by high electron fluences. Both AO and electron fluences at high energies should be reassessed for the TSS-1 reflight mission.

REFERENCES

1. Siegfried, D.E.: "A Phenomenological Model for Orificed Hollow Cathodes." NASA CR-168026, December 1982.

2. Cuthbertson, J.W., Langer, W.D., Motley, R.W., and Vaughn, J.A.: "Atomic Oxygen Beam System for Erosion Simulation." NASA CP-3103, vol. II, June 1990, pp. 734–40.

3. Vaughn, J.A., et al.: "Characterization of a 5 eV Neutral AO Beam Facility." NASA CP-3103, vol. II, June 1990, pp. 764–70.
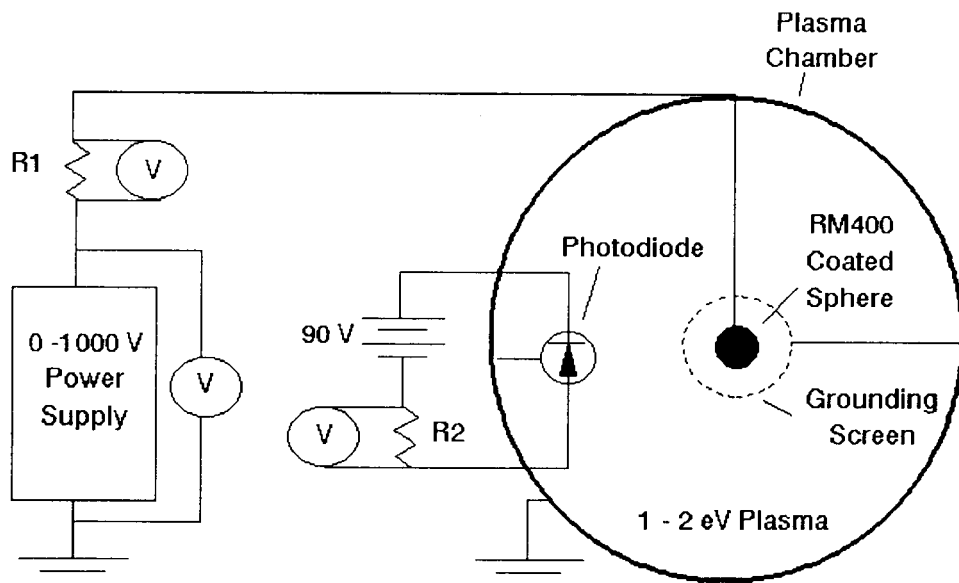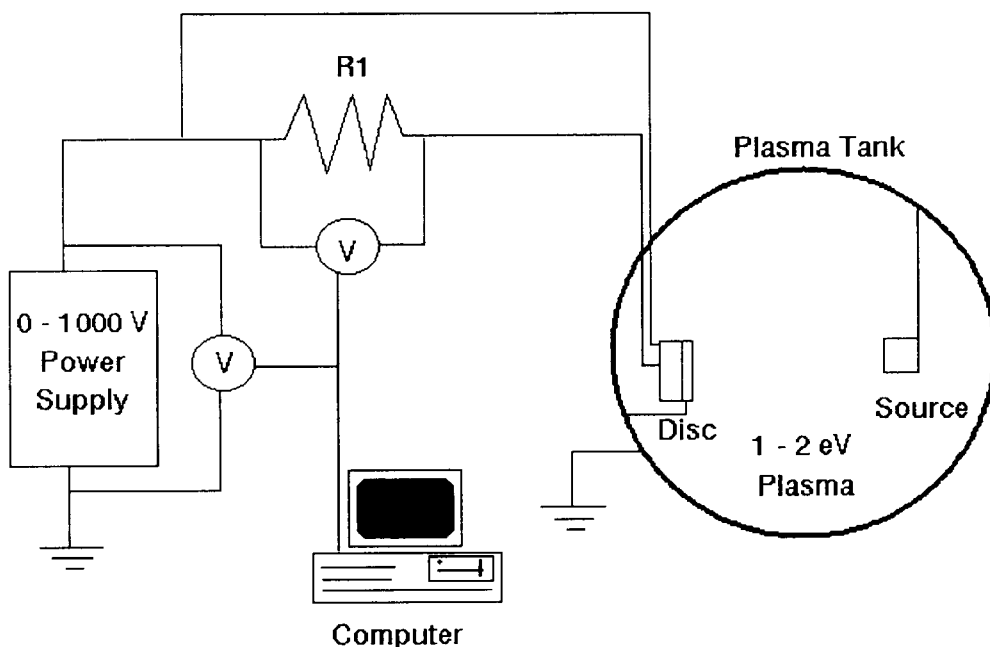
Figure 1. RM400 luminescence test apparatus.

Figure 2. RM400 high-energy electron exposure tests apparatus.

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Cross-section of aluminum carrier for RM400 paint tests

Conductors
connected to
bias voltage

(A)

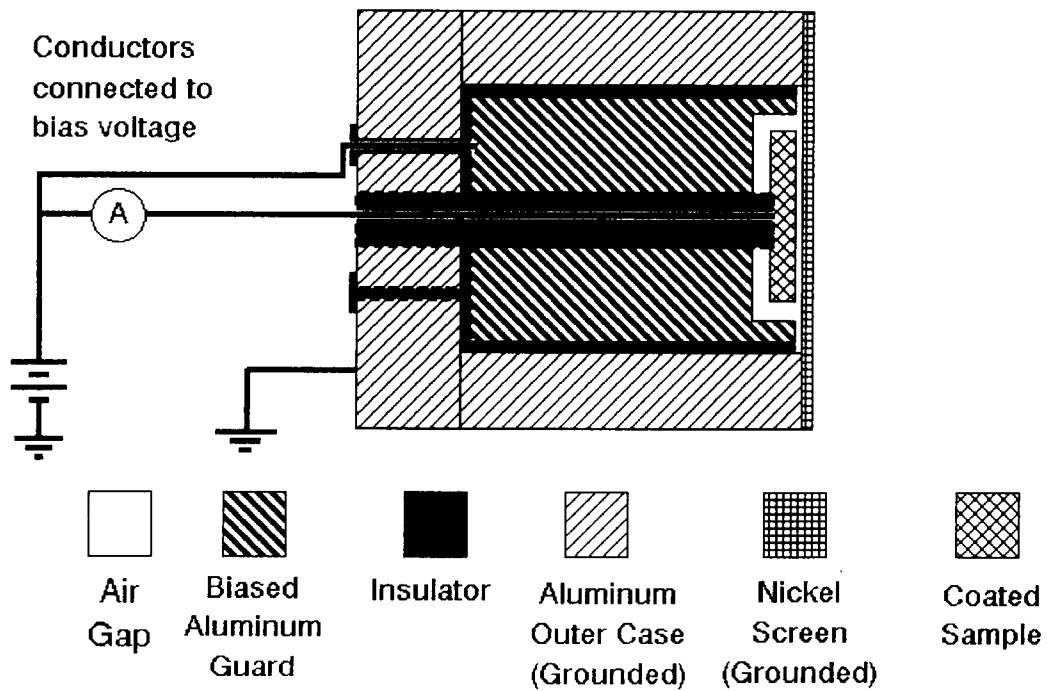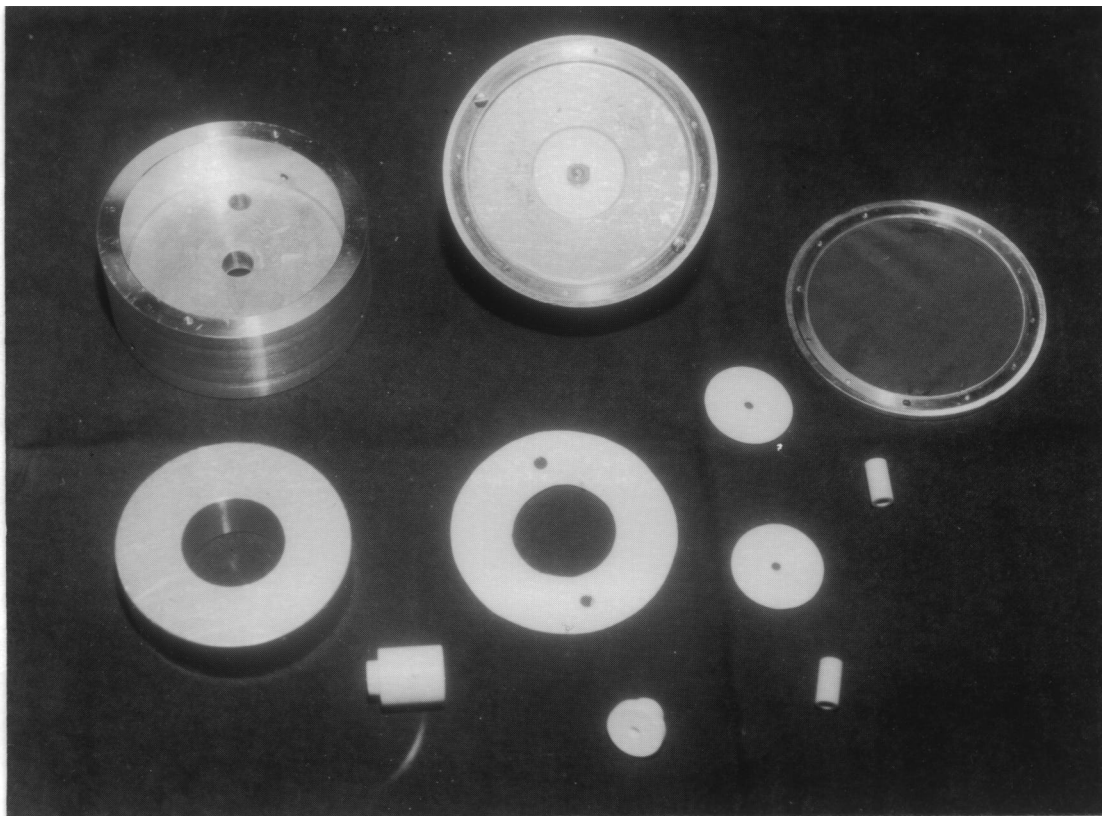|					
Air Gap	Biased Aluminum Guard	Insulator	Aluminum Outer Case (Grounded)	Nickel Screen (Grounded)	Coated Sample

Figure 3. Schematic of high-energy electron sample carrier.

Figure 4. Photograph of assembled high-energy electron sample carrier.

TSS-1 RM400 TC Coating
Current vs Voltage for Each Screen

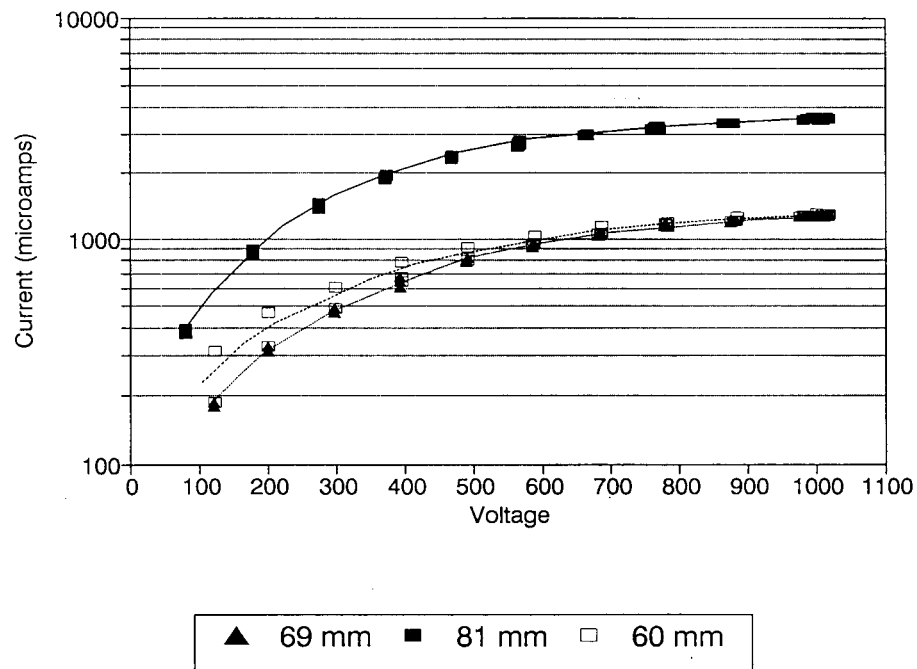▲ 69 mm   ■ 81 mm   ▫ 60 mm

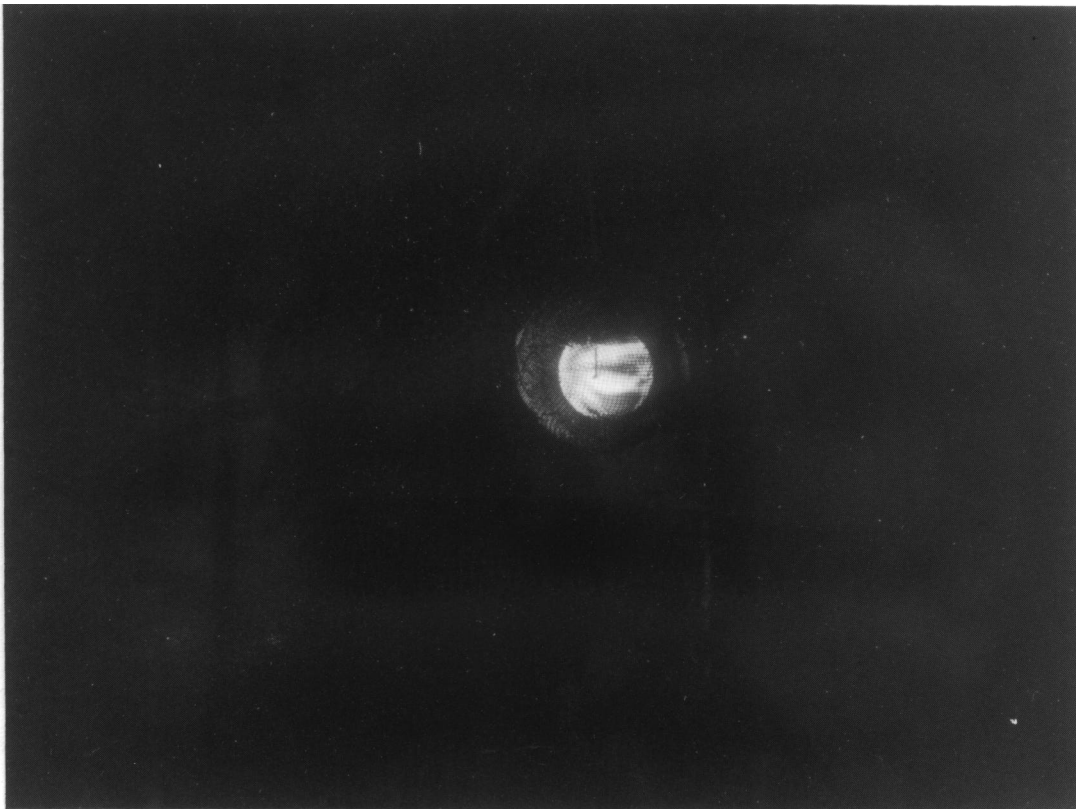Figure 5. Typical current versus voltage for three different grounding screens.

Figure 6. Photograph of RM400 coated sphere in plasma chamber with 750-V bias.

TSS-1 RM400 TC Coating
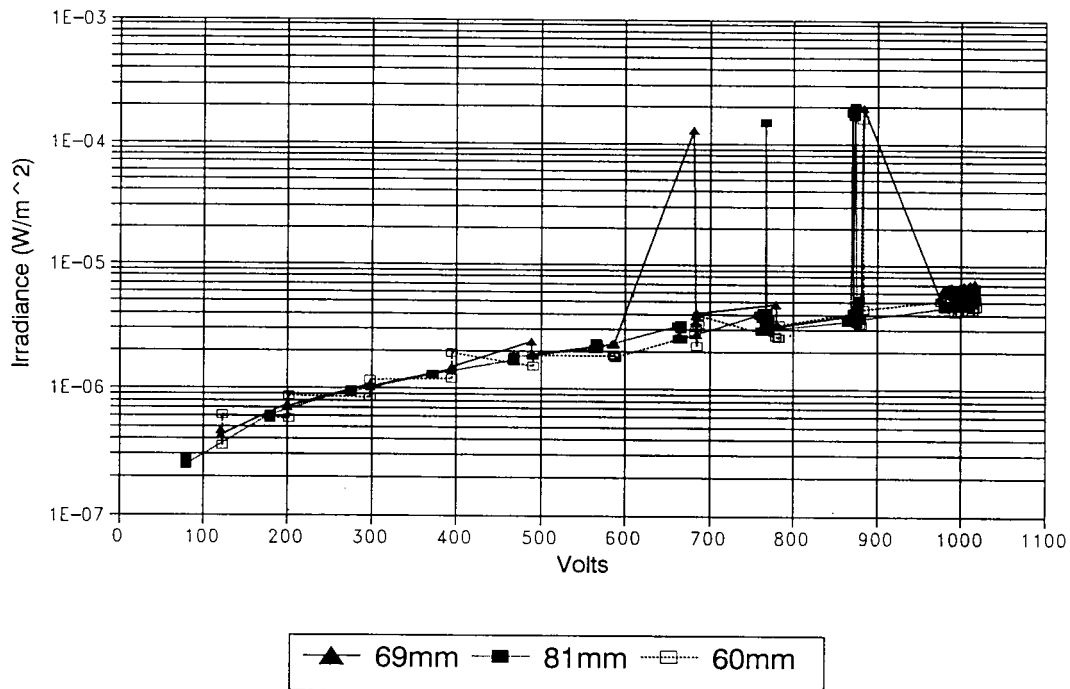## Sphere Luminescence vs Electron Energy

Figure 7. RM400 coated sphere irradiance data for three different size grounding screens.

TSS-1 RM400 Thermal Control Coating
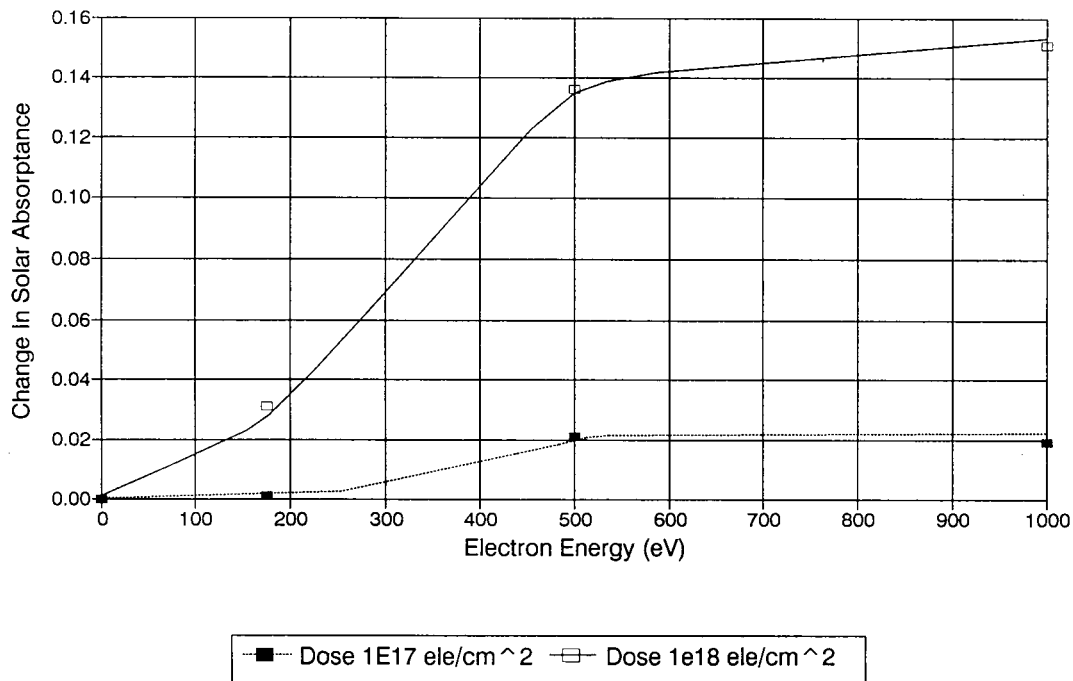## Absorptance Change Due to Electron Exp.

Figure 8. Change in solar absorptance due to electron exposure.

TSS-1 Thermal Control Coating
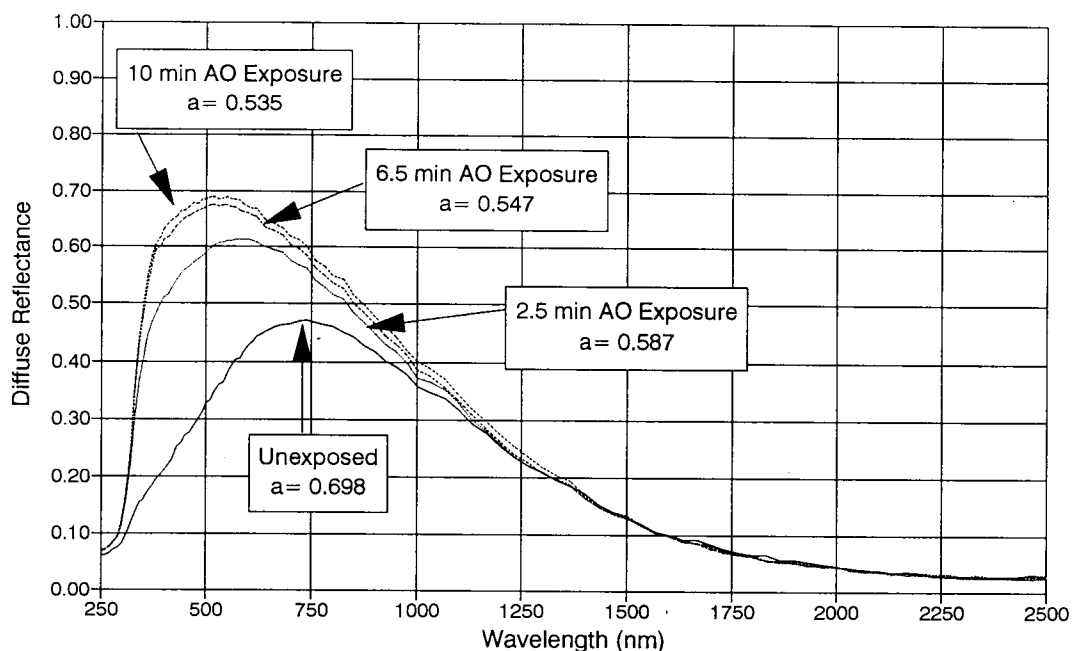### After AO Exposure for Cleaning--RM9

Figure 9. Typical diffuse reflectance curves for AO cleaning of RM400.

TSS-1 Thermal Control Coating
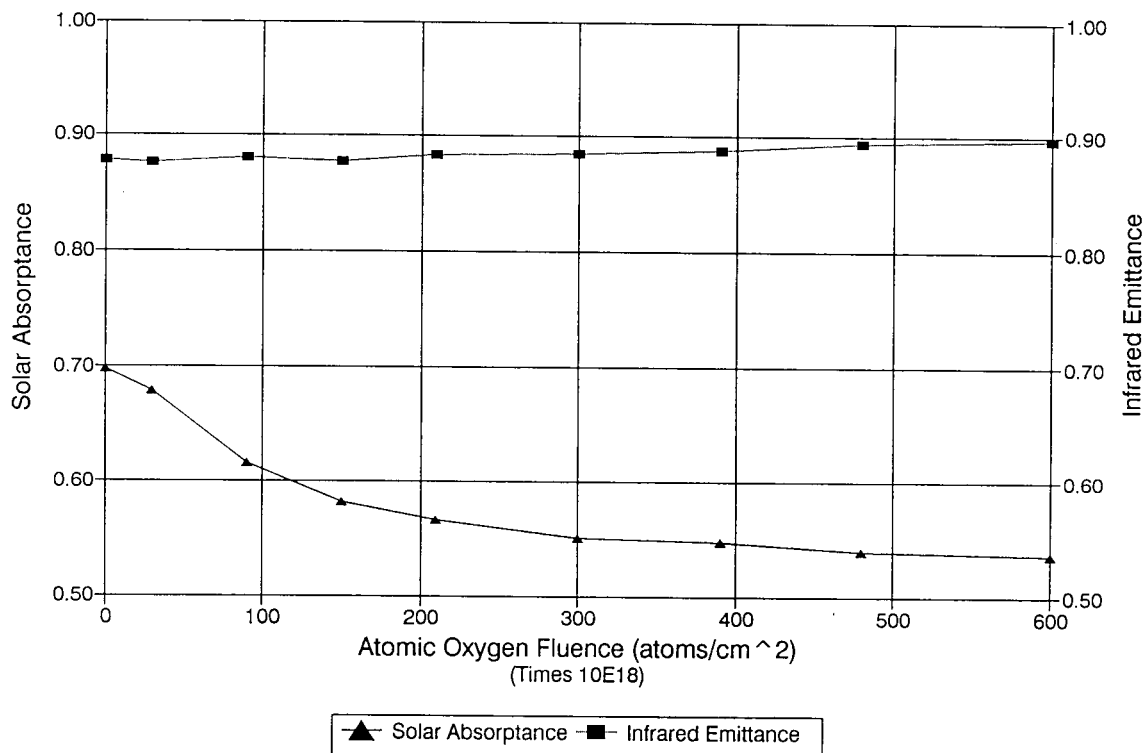### AO Exposure After Electron Exposure-RM9

Figure 10. Solar absorptance and infrared emittance data for AO cleaning of RM 400.

Table 1. Thermal control property changes due to current density and
electron energy on RM 400.

Sample No.	BOL Optical Properties	After AO Exposure $(2\times10^{19}$ a/cm$^2)$	After Electron Exposure 175 eV $(10^{17}$ ele/cm$^2)$	After Electron Exposure 175 eV $(10^{18}$ ele/cm$^2)$	After Electron Exposure 500 eV $(10^{17}$ ele/cm$^2)$	After Electron Exposure 500 eV $(10^{18}$ ele/cm$^2)$	After Electron Exposure 1,000 eV $(10^{17}$ ele/cm$^2)$	After Electron Exposure 1,000 eV $(10^{18}$ ele/cm$^2)$
RM-1 Control	$\alpha = 0.573$ $\varepsilon = 0.865$							
RM-2	$\alpha = 0.580$ $\varepsilon = 0.861$	$\alpha = 0.548$ $\varepsilon = 0.875$						
RM-3	$\alpha = 0.577$ $\varepsilon = 0.860$	$\alpha = 0.561$ $\varepsilon = 0.886$						
RM-4	$\alpha = 0.575$ $\varepsilon = 0.862$	$\alpha = 0.548$ $\varepsilon = 0.875$					$\alpha = 0.567$ $\varepsilon = 0.876$	
RM-5	$\alpha = 0.574$ $\varepsilon = 0.862$	$\alpha = 0.547$ $\varepsilon = 0.876$						
RM-6	$\alpha = 0.561$ $\varepsilon = 0.872$	$\alpha = 0.549$ $\varepsilon = 0.873$			$\alpha = 0.570$ $\varepsilon = 0.875$			
RM-7	$\alpha = 0.580$ $\varepsilon = 0.862$	$\alpha = 0.560$ $\varepsilon = 0.876$	$\alpha = 0.558$ $\varepsilon = 0.876$					
RM-8	$\alpha = 0.583$ $\varepsilon = 0.861$	$\alpha = 0.561$ $\varepsilon = 0.874$		$\alpha = 0.589$ $\varepsilon = 0.877$				
RM-9	$\alpha = 0.578$ $\varepsilon = 0.865$	$\alpha = 0.556$ $\varepsilon = 0.877$						$\alpha = 0.707$ $\varepsilon = 0.876$
RM-10	$\alpha = 0.578$ $\varepsilon = 0.862$	$\alpha = 0.551$ $\varepsilon = 0.876$				$\alpha = 0.687$ $\varepsilon = 0.875$		

APPROVAL

**LABORATORY ELECTRON EXPOSURE OF TSS-1 THERMAL
CONTROL COATING**

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The information in this report has been reviewed for technical content. Review of any informa-tion concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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P.H. SCHUERER
Director, Materials and Processes Laboratory